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An Evaluation of Direct Readout Infrared Data

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ABSTRACT—The appearance of clouds in the video and the 11.5- and 6.7-μm infrared satellite bands is compared with contemporary observations taken aboard a jet reconnaissance aircraft. Attempts are made to extract temperatures from satellite infrared imagery by comparing the brightness of the target with the calibration step wedge transmitted by the satellite. In the presence of the type of cirrus clouds observed on the flights, satellite-measured cloud-top temperatures are misleading due to the transmissivity of cirrus. However, most cirrus are easily recognized in the facsimile presentation by their appearance and organization. Some cirrus observable from the air cannot be seen either from the ground or in the video and 11.5-μm satellite bands. This so-called "invisible" cirrus presents no weather or flight hazard; but according to earlier investigators, this could cause errors in the interpretation of temperature data. The 6.7-μm channel offers hope of identifying areas of invisible cirrus and thus the possibility of correcting for its effects.

1. INTRODUCTION

During May 4–15, 1970, an intensive observational program was conducted to compare the characteristics of clouds as they appeared to several types of sensors. The program was called "Cloud Truth" and involved the Environmental Science Services Administration (ESSA),[1] the National Aeronautics and Space Administration (NASA), the U.S. Air Force, the U.S. Navy, The University of Chicago, and Continental Airlines. Simply, the purpose of the program was to compare cloud heights and temperatures as deduced from satellite 11.5-μm infrared (IR) data with "true" values based on simultaneous aircraft, TPQ–11 vertically pointed radar, and lidar measurements.

The objectives of the Air Force Cambridge Research Laboratories' (AFCRL) experiment were to measure the height and temperature at the tops of cirrus clouds and compare these temperatures with those measured from direct readout infrared (DRIR) "pictures." The possibility of extracting quantitative data from the DRIR may seem like an exercise in futility to people familiar with the electrolytic facsimile output; however, at the AFCRL, a Muirhead K300–A/1 photofacsimile recorder [2] has been modified to the point where such a possibility may be a practical goal. The modifications double both the length and width of the DRIR display and precisely control the relationship between a satellite's signal and the photographic output. The ability to match the signal range to the photographic range is critical in the DRIR because the signal range is so small in the temperature range of clouds. Temperatures are extracted from the DRIR picture using the calibration gray-scale wedge transmitted between sweeps of the sensor across the earth. This wedge relates photographic tone to six discrete temperature values.

[1] Now the National Oceanic and Atmospheric Administration (NOAA)

[2] Mention of a commercial product does not constitute an endorsement.

The intensity of the gray shades at the six calibrated steps are measured with a reflective densitometer; these values are plotted against the appropriate temperatures on a graph. From a curve drawn through these points, the value of temperature corresponding to any reflective density can be determined. The ⅛-in. diameter of the densitometer aperture covers an ellipse with axes of 25 and 35 mi at the satellite subpoint. The details of these modifications and the techniques for optimizing photographic output have been published recently (Myers et al. 1970).

2. AIRCRAFT OBSERVATIONS

The observational platform to provide the truth for this experiment was a WC–135 provided by the 55th Weather Reconnaissance Squadron of the 9th Weather Wing, Air Weather Service (McClellan Air Force Base, Sacramento, Calif.). It was equipped with the AMQ–25 meteorological system that provided a printout of time, location, radar altitude, temperature, and wind velocity at any selected interval greater than several seconds. Usually, printout was every 2 min. Dropsondes were used on some flights over water. About 320 black and white 35-mm photographs, some in stereo, were taken to document cloud conditions along the flight tracks.

Within certain constraints, the plan was to fly as close as possible to the tops of extensive areas of cirrus clouds near the time of the orbits of Nimbus 4 and the Improved TIROS Operational Satellite (ITOS) 1. The constraints were (1) the aircraft had to return to McClellan Air Force Base (AFB) in Sacramento, Calif., after each mission; (2) the aircraft was occasionally prevented from attaining optimum altitude by air traffic control; and (3) the flights had to be planned 12–18 hr in advance, largely without the support of satellite data. On each flight, it was generally possible to rendezvous during two orbits of a satellite and occasionally during two orbits from both the ITOS and the Nimbus.

Altogether, 28,000 mi were flown in 11 missions. Features investigated were cold, warm, and occluded fronts; polar and tropical jet streams; Gulf of Alaska Lows; and the vicinities of severe thunderstorms. The data sample, however, is limited by a lack of extensive thick cirrus and the availability of adequate DRIR coverage on only five flights.

The task of flying at cloud-top height to measure temperature with the Rosemont probe presented some difficulties. Most cirrus tops were diffuse or undulating. Telling exactly where the top was provided a challenge that could not be met completely within the restrictions of air traffic control. The procedure adopted, unless the area seemed very extensive, was to request a flight level estimated near the tops. If the aircraft was climbing, the altitudes of the tops were noted when passing through them. When the tops could not be reached, an estimate of the top would be made from the speed at which the texture of the cloud passed the overhead window. Likewise, if the aircraft descended to a level above the tops and it was determined that the next lower permissible flight altitude would be considerably within the clouds, the altitude of the tops was estimated from the speed at which cloud features passed beneath the aircraft. When there was reason to believe that a layer would be extensive enough to allow time to obtain clearance at several levels, the exact top of the cloud would be sought.

3. DIRECT READOUT INFRARED INTERPRETATION

General Considerations

When he uses the DRIR output, it is important for the analyst to be aware that he is looking at a thermograph and not a photograph since the temptation is strong to apply video interpretive procedures to IR data; this can be misleading. Figure 1 illustrates a simple but effective case. The left illustration shows the ITOS DRIR for a portion of nighttime orbit 1401 at approximately 0300 Pacific Standard Time (PST) on May 15, 1970. In this illustration, the coast of California between 40°N, 124°W and 31°N, 115°W is distinguishable because it is warmer (darker) than the Pacific Ocean. The colder Sierra Nevada Range (A), averaging 3000 m in elevation, contrasts sharply with the San Joaquin and Sacramento Valleys just to the west, which are near sea level. East of the Sierra Nevada Range, temperatures remain nearly the same as those in the mountains. The right illustration in figure 1 shows the same area the following afternoon on the ITOS daytime orbit 1407 at 1400 PST. The entire west coast and the Sierra Nevada Range are clearly outlined; the area to the east of these mountains is generally dark except for gray streaks associated with higher ridges or perhaps nearby clouds. A cursory examination of the left illustration in figure 1 might lead to the interpretation of a cloud deck over the Great Basin. Densitometer readings and the 1200 GMT 700-mb chart both support this interpretation with temperatures near 0°C over the area. A more careful examination of this illustration, however, reveals that Death Valley (B), the Grand Canyon (C), and the Great Salt Lake (D) show as warm spots indicating no general cloudiness over the area. This is verified by the 1200 GMT sea-level chart that shows clear to scattered cloud conditions and temperatures 2°–3°C above freezing. During the day, the satellite-measured temperatures were about 38°C as compared with shelter temperatures in the range of 20°–25°C.

Thus the change in the satellite data from night to day is not a change in cloudiness but is merely a reflection of variation in ground-surface temperature under conditions of strong radiational cooling and heating.

Clouds Associated With a Subtropical Jet and Closed Cells

The flight of May 4 that departed McClellan AFB at 1830 GMT and returned at 2315 GMT seemed uneventful at the time because no extensive layers of thick cirrus were encountered. The primary purpose of the flight was to document the structure and turbulence characteristics of "fishbone" cirrus, which are transverse bands frequently associated with subtropical jet streams. In figure 2, the jet stream was located along the band of clouds at the southern tip of the flight track. There was no associated fishbone cirrus; and despite the fact that many of the missions traversed moderate jet streams, there was no significant turbulence on this flight or on any of the flights.

Comparison of figures 2A and 2B reveals considerable differences between cloud forms. Many clouds barely detectable in the video (fig. 2A) are prominent in the IR (fig. 2B). The bright clouds of figure 2B have the texture and general configuration of cirrus. A rough estimate of the temperatures of these clouds based on visual comparison with the calibration wedge[3] places them between the gray shades for −19° and −56°C. For the most part, they appear closer to −19°C. Some small areas could have been colder, but they are too small to isolate even by this method. The flight data confirm that these clouds were indeed cirrus. At 37,000 ft, the aircraft was close to the tops of cirrus clouds of varying density and extent. Temperatures were within a few degrees of −55°C. Figure 3 is typical of the conditions; it shows a cirrus band with tops rising nearly to flight level, patches of lower cirrus, and some low scattered cumulus. The cirrus clouds encountered on this flight had emissivities considerably less than 1, with the possible exception of patches too small to detect in the DRIR presentation.

As the high clouds dominate the DRIR picture, the low clouds stand out in the video. The cellular cloud field easily identified in the video (fig. 2A) appears as a stratus deck in figure 2B because of the lower spatial resolution of the IR sensor. Actually, close inspection of the original DRIR print reveals very fine threadlike breaks in the cloud deck. These breaks probably would

[3] The densitometer could not be used on these clouds because there was no homogeneous area large enough to fill the ⅛-in. aperture of the instrument.

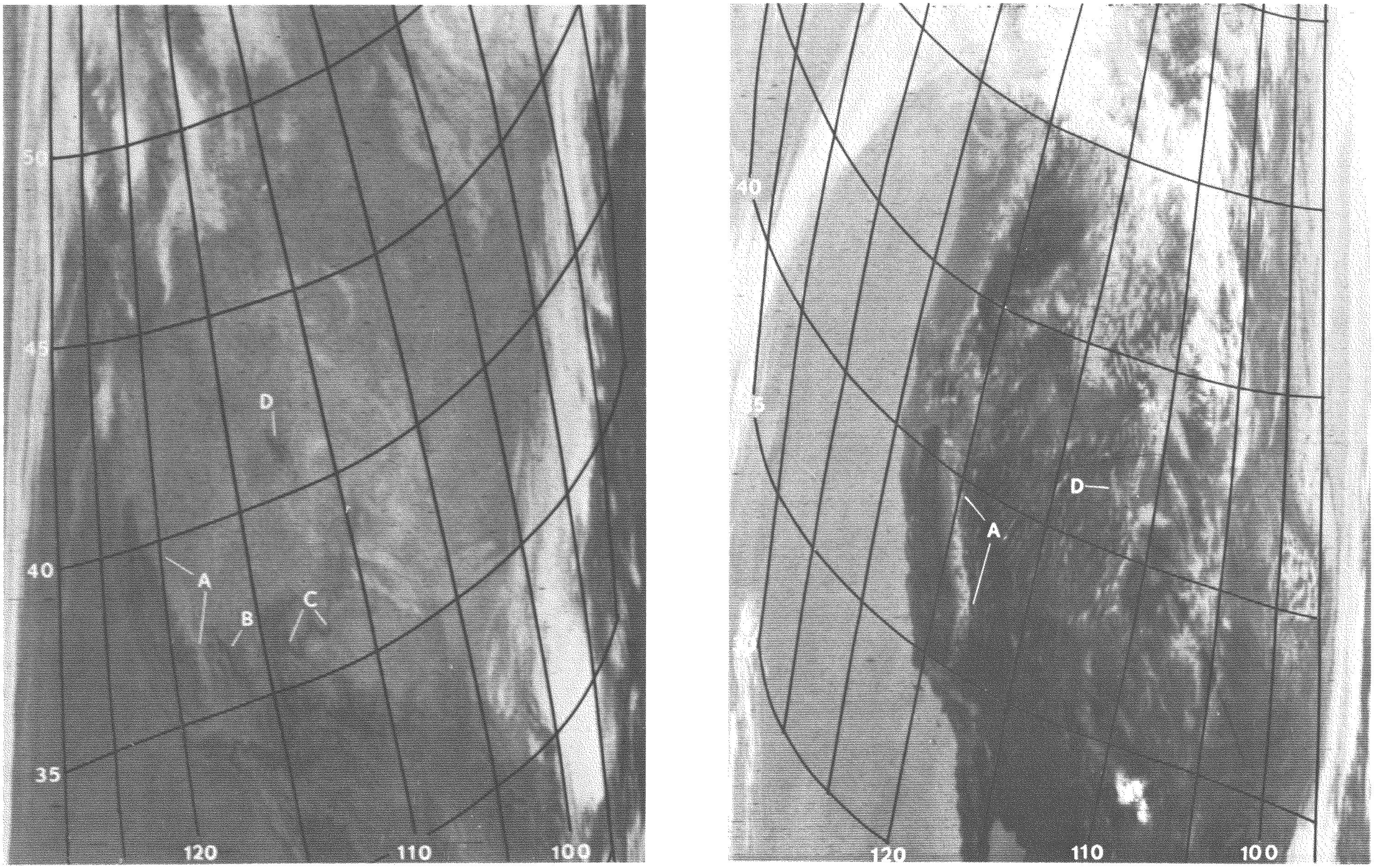

FIGURE 1.—ITOS 1 DRIR illustrating diurnal radiation changes on May 15, 1970; (left illustration) approximately 1100 GMT (0300 PST); (right illustration) about 2300 GMT (1500 PST); (A) Sierra Nevada Range; (B) Death Valley; (C) Grand Canyon; and (D) Great Salt Lake.

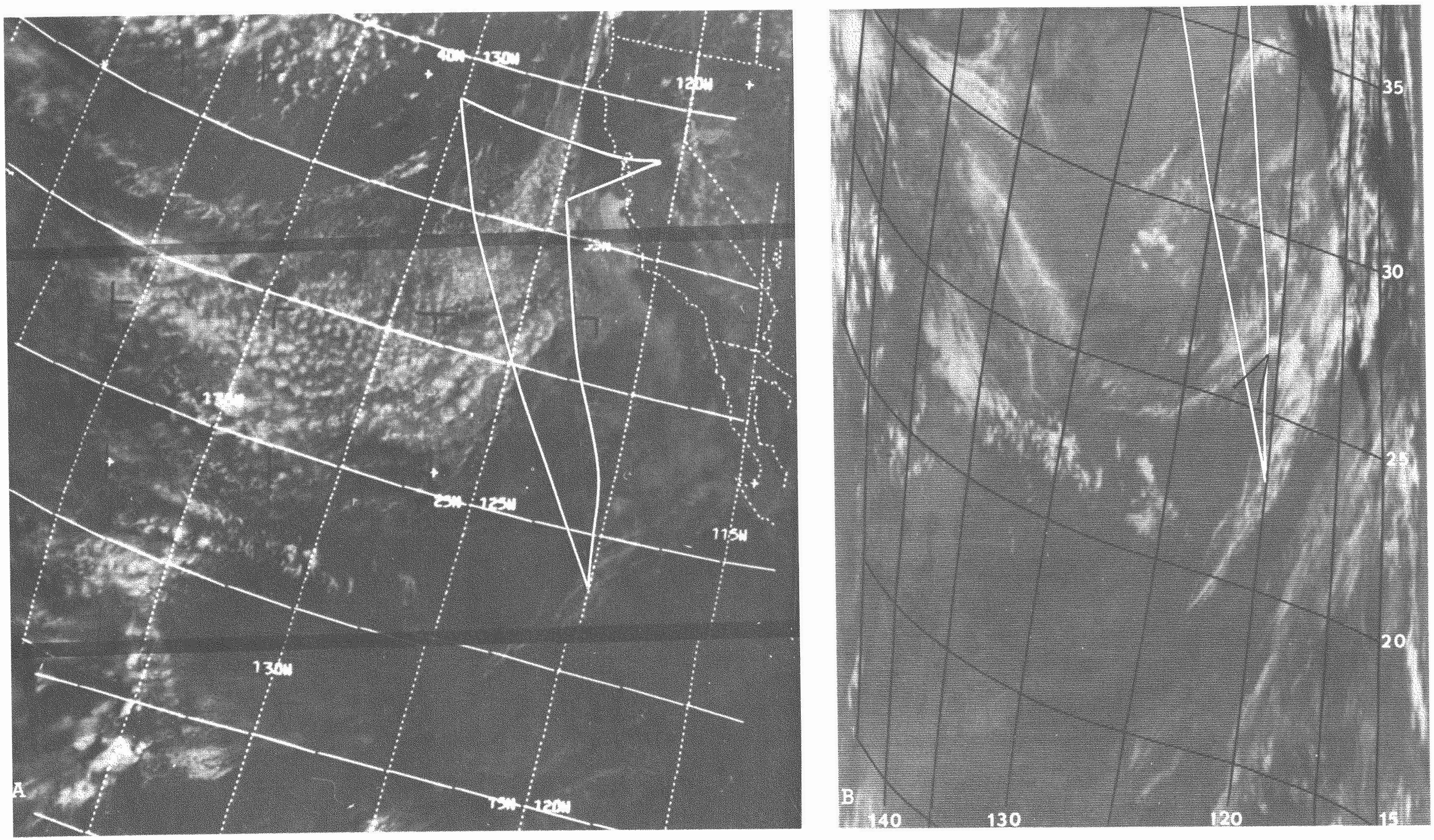

FIGURE 2.—(A) ESSA 9 Advanced Vidicon Camera System (AVCS) and (B) ITOS 1 DRIR for May 4, 1967, at about 2345 and 2320 GMT, respectively. The aircraft track on both (A) and (B) is indicated by prominent white lines along the west coast; the northern end of the DRIR was not recorded; and the black wedge on figure 2B is the approximate area of figure 3.

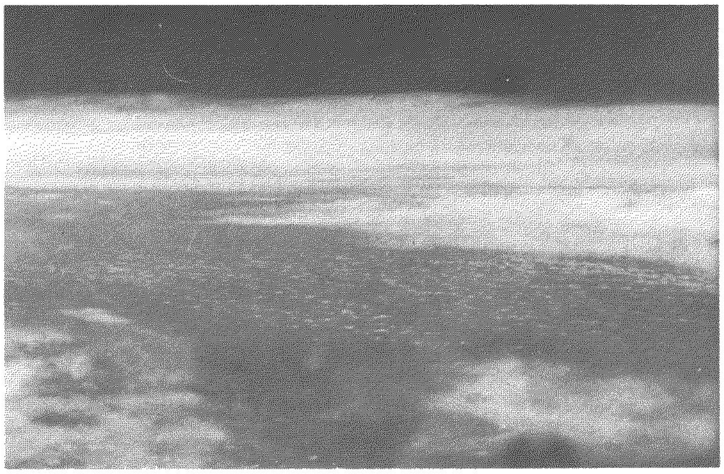

FIGURE 3.—Near-horizontal view toward the southwest at 2035 GMT on May 4, 1970, from a flight altitude of 37,000 ft and a camera base at 26°N,120.5°W. See also figure 2B.

not be detectable in an electrolytic facsimile product; but where high quality photographic or digital output is available, these breaks provide a useful clue to the identification of closed cells if video data are not available. In a similar manner, there are clues in the video to features best identified from IR data. Consider the cirrus line in figure 2B that crosses 135°W near 27.5°N. Because of the low clouds underlying that band, it cannot be located easily in figure 2A. Close examination of figure 2A, however, reveals that edges of the low-cloud elements are fuzzy and indistinct in the region of cirrus. Unfortunately, this effect is not always detectable as can be seen by comparing other regions of cirrus over low clouds.

The stratus deck off the coast in the vicinity of 35°N cannot be detected visually in the DRIR. The densitometer did sense a temperature change at that location but without confirmation from the video, it would be difficult to determine if the change was caused by a low-cloud edge or a cirrus cloud with an emissivity even lower than those in the general area.

The subjective interpretation of conditions derived from the video and IR presentations agree qualitatively with the observed conditions. Objective processing of the IR data, however, would have produced some very misleading moderately high temperatures associated with the cirrus clouds. Most cirrus would not have been identified because temperatures would have corresponded to fictitious layers of low and middle clouds as discussed by Valovcin (1968) in his paper on cirrus emissivity.

Thin and "Invisible" Cirrus

Appleman (1961) reported aircraft observations of very thin cirrus that could not be detected when viewed from high angles but seemed like a fairly thick sheet when viewed from an aircraft at a low angle. Later, Zdunkowski et al. (1965) performed an extensive theoretical study to determine if such an invisible cloud could be responsible for sudden decreases in the net infrared flux measured by radiometersondes near the tropopause. They concluded

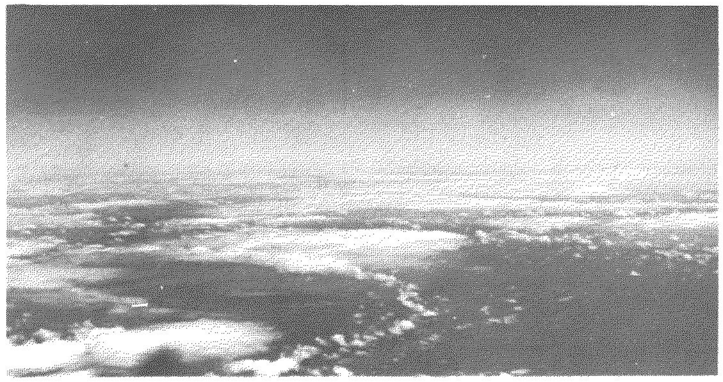

FIGURE 4.—Near-horizontal view toward the south-southeast at 2108 GMT on May 6, 1970, from a flight altitude of 34,000 ft and a camera base at 27.0°N, 120.5°W. Note the gradual brightening of the sky toward the horizon. See also figure 6.

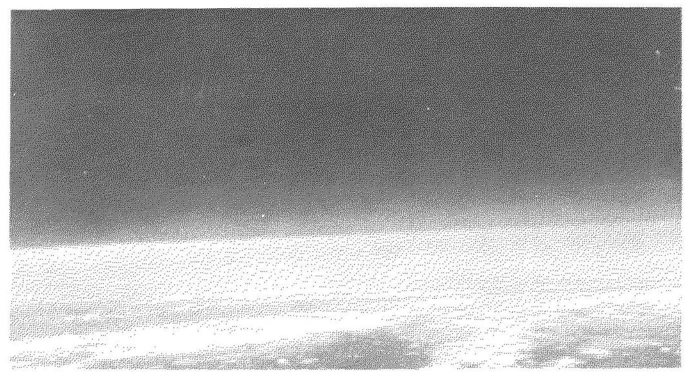

FIGURE 5.—Near-horizontal view toward the north-northeast at 2224 GMT on May 6, 1970, from a flight altitude of 35,000 ft and a camera base at 31°N, 125°W. Note the apparent high-cloud deck in the distance. See also figure 6.

that an ice crystal but not a dust cloud could meet the criteria. The particular sizes and concentrations used in their computations led to "appreciable attenuation effects in the infrared region" resulting from cirrus clouds transparent in the visible band. Their calculations showed that, in a tropical air mass, clouds of this type would reduce the total net flux by 10 percent and the upward flux in the 6.0- to 6.5-μm band by 9 percent and that, in the 8–12 μm band, a satellite would sense the same ground-level temperature 4°C lower when invisible cirrus was present than when it was not. In midlatitudes and polar regions, the reductions would be progressively less.

On almost every flight, conditions were observed that could have been caused by a cirrus cloud which was so thin that it would not be noted by a ground observer. The conditions consisted of excellent vertical visibility with no indication of clouds anywhere near the aircraft. Horizontally, the visibility would also be considered unrestricted although the aircraft appeared to be in the center of a circular clearing fifty to several hundred miles in radius in an extensive cirrus deck. That this was not the case would become apparent after several minutes when it could be noticed that the distance to the apparent edge

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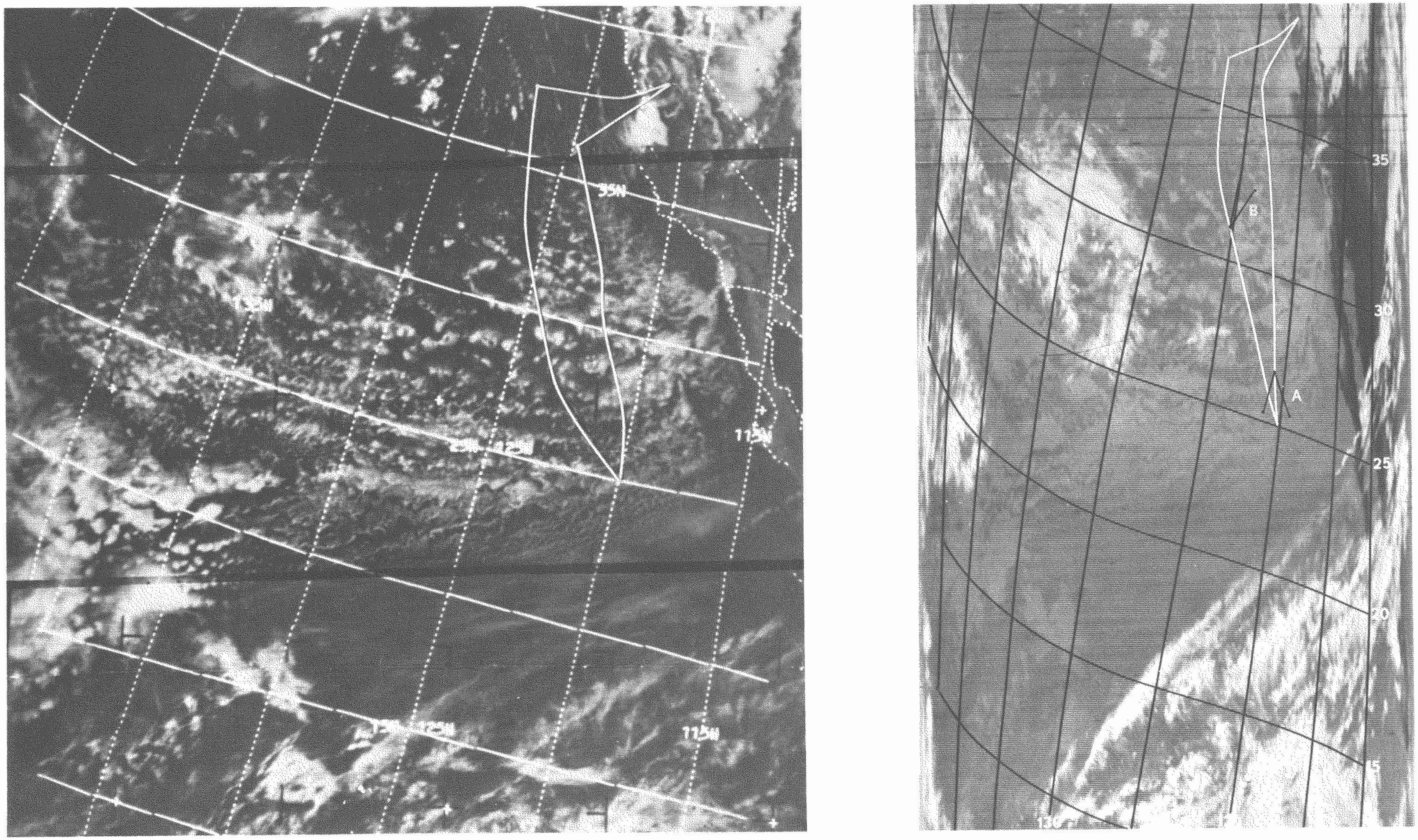

FIGURE 6.—ESSA 9 AVCS (left illustration) and the ITOS 1 DRIR (right illustration) at approximately 2245 and 2315 GMT, respectively, on May 6, 1970. The aircraft track is indicated by the prominent white lines along the west coast; wedges A and B on the right illustration are the approximate areas of figures 4 and 5, respectively.

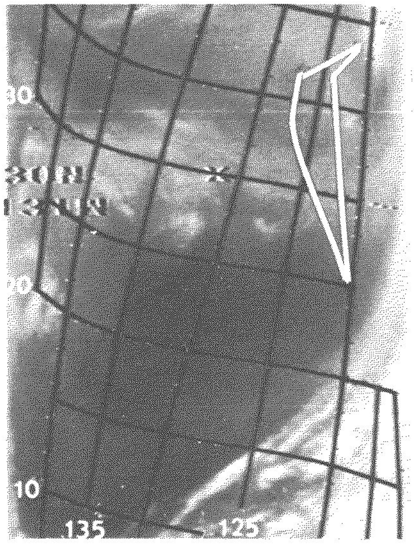

FIGURE 7.—Nimbus 4, 6.7-μm channel at approximately 2015 GMT on May 6, 1970. The aircraft track is indicated by the prominent white lines.

of the cirrus deck never changed in any direction. Figures 4 and 5 are typical of conditions in clear air and what is believed to be invisible cirrus. In figure 4, the sky gradually brightens toward the horizon; in figure 5, the view appears to be directed toward the edge of or perhaps slightly below a deck of high clouds in the distance.

The May 6 flight was conducted almost entirely in conditions of cirrus that were undetectable in the satellite video (left illustration in fig. 6) and the DRIR (right illustration in fig. 6) and were certainly not obvious from the aircraft except for a few bands that were too narrow to be isolated by the satellite sensors. It is not until the 6.7-μm channel data are examined (fig. 7) that what may be the invisible clouds can be seen. The 6.7-μm channel measures radiance in the water-vapor absorption band; its purpose is to give information on the moisture content of the upper troposphere and stratosphere. The lower the radiance, the lower the temperature at which energy is emitted in this band and the lighter the shade of the imagery in figure 7. Comparing figure 7 with the right illustration in figure 6, one can see that the cirrus clouds identifiable in the 11.5-μm band also appear as clouds in the 6.7-μm band. These clouds are imbedded in a diffuse field of gray in figure 7. This diffuse gray should indicate water vapor in the upper troposphere. Theoretically, if the water vapor were at the same level as the clouds, it would have the same gray shade; but it is darker and thus should represent a lower layer. However, according to Fritz and Rao (1967), water vapor does not emit as a blackbody at temperatures below $-40°C$. Since the few small visible cirrus clouds observed on this flight were slightly above the aircraft (35,000 ft, $\sim -50°C$), it is reasonable to assume that the diffuse gray represents "gray" body radiation from a *layer* near the clouds and not blackbody emission from water vapor at a lower altitude. The flight log, which of course was compiled without any knowledge of the appearance of the 6.7-μm data and without intent to locate invisible clouds, notes improved visibility in the dark area in figure 7 at the southern end of the flight and on both legs in the darker band between 32° and 34°N. The right illustration in figure 6 identifies the location of the clear-air (A) and invisible cirrus (B) regions illustrated in figures 4 and 5, respectively.

No optical phenomena such as halos were noted during the flight; but considering that there is a limited view from an aircraft and that halos were not being sought, their presence is not precluded. On the basis of these observations, it would seem that invisible cirrus is what Zdunkowski et al. (1965) theorized it could be (i.e., an ice-crystal cloud composed of particles of a size and distribution that render it difficult to see at high and medium viewing angles). Verification of whether the diffuse gray areas in the 6.7-μm data are the cause of the abrupt changes they noted in the radiation flux could be made by examining the 6.7-μm energy level at points where radiometersonde flights are made and determining if it has a systematic relationship with the magnitude of the change in flux in the upper troposphere. It might also be possible to determine the effect of invisible cirrus on the window temperatures directly in cases where there is a strong 6.7-μm temperature gradient overlying an otherwise cloudless and thermally homogeneous emitting surface such as would be found in parts of the ocean.

Polar Jet Stream Cirrus

The May 14 flight across a jet stream was the only one for which DRIR data were available that had masses of cirrus clouds which appeared reasonably homogeneous over a large-enough area to attempt a densitometer reading. Figure 8 shows the flight track and densitometer-derived temperatures on the DRIR picture. Between 47° and 50°N, the aircraft was at 33,000 ft on the northbound (western) leg and 36,000 ft on the eastbound and southbound legs. The satellite data are approximately 3 hr later than the aircraft data.

The cloud conditions along the flight path were variable. At 33,000 ft, conditions ranged from cirrus thick enough to obscure both ground and sky to a cirrus layer of variable density with patches and bands of cirrus above. At 36,000 ft, the aircraft still did not get above all the clouds but was near the top of the highest layer of any extent. There were some patches of higher cloud; and occasionally, the layer nearest the aircraft would become dense or thick enough almost to obscure the blue sky. In summary, the encountered cirrus associated with this jet stream consisted of at least three layers between approximately 30,000 and 40,000 ft. The optical density of the clouds in each layer varied greatly along the flight path. At times, there was only very thin cirrus at all levels; at other times, two or more layers appeared to merge to form a deep layer of dense cloud.

Aircraft temperatures measured at 33,000 ft along the northbound leg were $-51°C \pm 1°$; at 36,000 ft along the other two legs, they were $-58°C \pm 1°$. The cloud-top temperatures therefore had to be $-58°C$ or lower. The

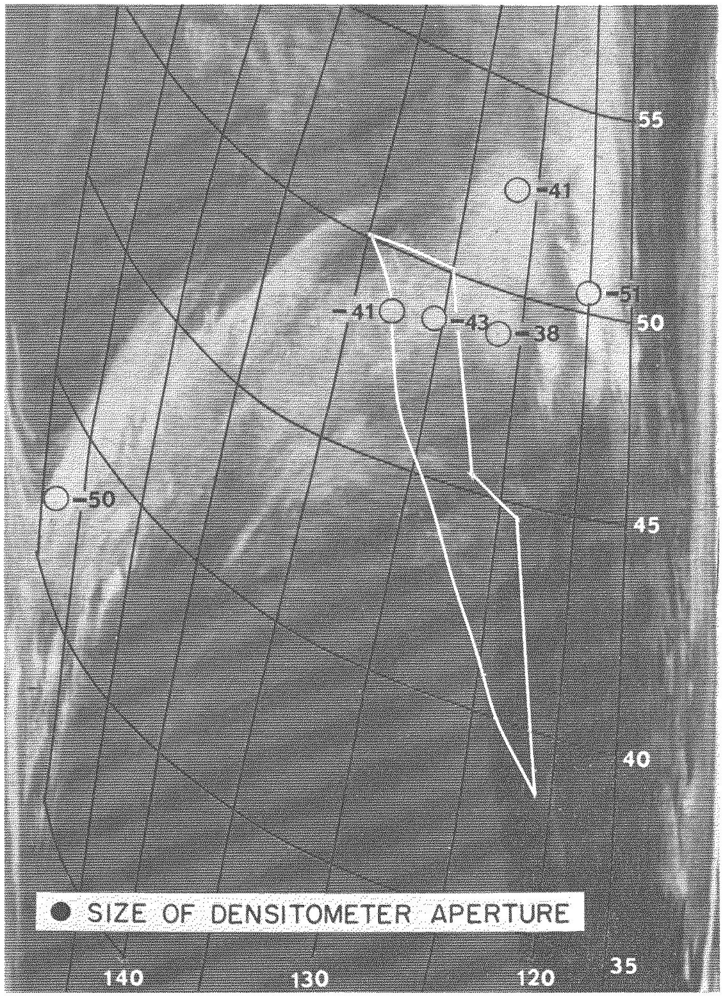

FIGURE 8.—ITOS 1 DRIR at approximately 2310 GMT on May 14, 1970. The aircraft track is indicated by the prominent white lines; the black numbers are densitometer-measured temperatures (°C) at indicated points.

DRIR-derived temperatures from the coldest parts of the cirrus field ranged from −38° to −51°C as indicated in figure 8. As regards these temperatures, however, none of the sampled areas had a completely uniform gray shade even to the eye; even if they represented blackbody emission, they can be expected to indicate higher temperatures than those of the coldest clouds within the densitometer aperture.

It should be noted that the lowest temperatures were observed toward the edge of the picture, where the geometry of the viewing would increase the height of the emission layer of clouds that were not blackbodies and thus decrease their radiating temperature.

Whether clouds of the type observed on this and other flights contain elements that radiate as blackbodies and are large enough to detect by more refined techniques is an important problem. These coldest spots could be used as indicators of the general cloud-top temperature in the area, although variations about this temperature more likely represent variations in cloud emissivity than altitude. When geosynchronous satellite IR data are available, the temperatures of these cold patches could be reliably used to assign altitudes to wind vectors derived from their motions.

4. CONCLUSIONS

The effect of sun and viewing angle on ground-observer estimates of the extent, opacity, and even presence of cirrus has long been known. The results of this experiment verify that observational difficulties are also present in both video and infrared satellite-detection of cirrus. As cirrus transmits light, it also transmits heat; and with the possible exception of anvils (not covered in this study), there are only small patches where it seems opaque to heat from below. In general, however, cirrus clouds that have any significance to, at least, routine subsonic flight operations can be identified in the DRIR presentation by their shape and distribution.

Data to establish a significant quantitative relationship between DRIR brightness and cirrus-top temperatures did not result from this experiment. Dense cirrus were not encountered along the flight paths in sufficiently large masses to make densitometer readings representative of cloud-top temperatures even in the polar jet stream case. Thus, if conditions encountered on this series of flights are typical, the determination of cirrus temperatures or altitudes will be a very difficult task. The higher spatial resolution possible with machine-processed temperatures would enable the specification of the temperatures in much smaller patches of dense cirrus than can be measured by the densitometer. The temperatures of these small patches could be considered representative of the surrounding cirrus field if further experimentation determined that these small elements were reliable indicators of blackbody temperature.

The 6.7-μm channel provides further qualitative information in its pictorial presentation. It verifies the identification of higher clouds and defines regions of water vapor at high altitudes. It is very possible that this high-level water vapor is the phenomenon known as invisible cirrus that is capable of causing errors in the 11.5-μm temperature data. It is not possible to state categorically that the water-vapor channel isolates cirrus clouds alone. Certainly, cirrus will show up bright and sharply defined in the 6.7-μm photographic presentation; but examination of wintertime cloud data reveals that high middle clouds also can be well-defined in the presence of a dry upper troposphere.

It is evident, on one hand, that a comprehensive qualitative description of the clouds can be made from the photographic presentations of the three channels. Actually, for most weather station applications, the automatic picture transmission (APT) and DRIR provide sufficient information.

On the other hand, computer processing of the data presents quite a programming challenge. The subjective decisions that come so easily to a man are difficult to reach on a computer. The results, however, would have much broader application. One could try to program the computer to duplicate human logic by a series of decisions that can be illustrated by reference to figures 6 and 7. Of course, for objective processing, numercial values would have to be assigned to the temperatures, and brightness would have to be represented in the pictures.

The cold areas of figure 7, such as those near 30°N and the lower right corner would be identified as cirrus-cloud regions. Since most of these clouds do not radiate as blackbodies, their temperatures would be estimated from their 11.5-μm temperature and satellite vertical sounding data by using the techniques suggested by Valovcin (1968) or perhaps by a sampling of the coldest spots as suggested earlier. The warm area, running from the center right to the lower left, would be defined as a region from which reliable blackbody temperatures could be extracted from the digitized version of the 11.5-μm data in the right illustration of figure 6. The cool regions of figure 7 would have to be tested by some, as yet, undefined process to determine if they represent high middle clouds, water vapor alone, or water vapor and ice crystals (invisible cirrus). If the latter is the case, a correction would be applied to 11.5-μm temperatures in the cool region to account for the attenuating effects of the invisible cirrus. The video data, by virtue of its higher spatial resolution, can be used to refine the identification of low and middle clouds and to locate areas where the 11.5-μm temperatures result from averaging surface and cloud temperatures because the clouds or breaks between them are beyond the resolution of the radiometer. Video data would also be required to identify conditions of strong surface inversions and ground fog that cannot be unambiguously interpreted in the IR. In the former case as seen in figure 1, a nonexistent layer of clouds is suggested; in the latter, the fog could not be distinguished from the surface.

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